

SOHO uncovers solar secrets

Space weather, comets and the Sun's interior

by Pål Brekke, Bernhard Fleck, and Stein Haugan

SOHO, the Solar and Heliospheric Observatory, is a project of international cooperation between ESA and NASA to study the Sun, from its deep core to the outer corona and the solar wind. It carries a complement of 12 sophisticated instruments, developed and furnished by 12 international consortia involving 39 institutes from 15 countries. Since its launch on 2 December 1995, SOHO has provided an unparalleled breadth and depth of information about the Sun - from its interior, through the hot and dynamic atmosphere, out to the solar wind. SOHO continues to transmit high quality data, even after the dramatic loss and recovery in 1998 and 1999. New and interesting results are adding to the large number of exciting discoveries made by SOHO since the first observations in 1996.

The SOHO spacecraft

The SOHO mission is a major element of the joint ESA/NASA International Solar Terrestrial Programme (ISTP). ESA was responsible for the spacecraft's procurement, integration and testing and it was built in Europe by an industry team lead by Matra Marconi Space (now called Astrium). NASA provided the launcher, launch services and ground-segment system and is responsible for in-flight operations following the launch. Mission operations are conducted from NASA/Goddard Space Flight Center (GSFC).

SOHO was launched by an Atlas II-AS from Cape Canaveral on 2 December 1995 and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996, six weeks ahead of schedule. Commissioning of the spacecraft and the scientific payload was completed by the end of March 1996. The launch was so accurate and the orbital manoeuvres were so efficient that enough fuel remains on board to maintain the halo orbit for several decades, many times the lifetime originally foreseen six years. An extension of the SOHO mission for a period of five years beyond its nominal life-time, i.e. until March 2003, was approved in 1997.

SOHO has a unique mode of operations, with a 'live' display of data on the scientists' workstations at the SOHO Experimenters' Operations Facility (EOF) at NASA/Goddard Space Flight Center, where the scientists can command



their instruments in real-time, directly from their workstations.

The solar interior

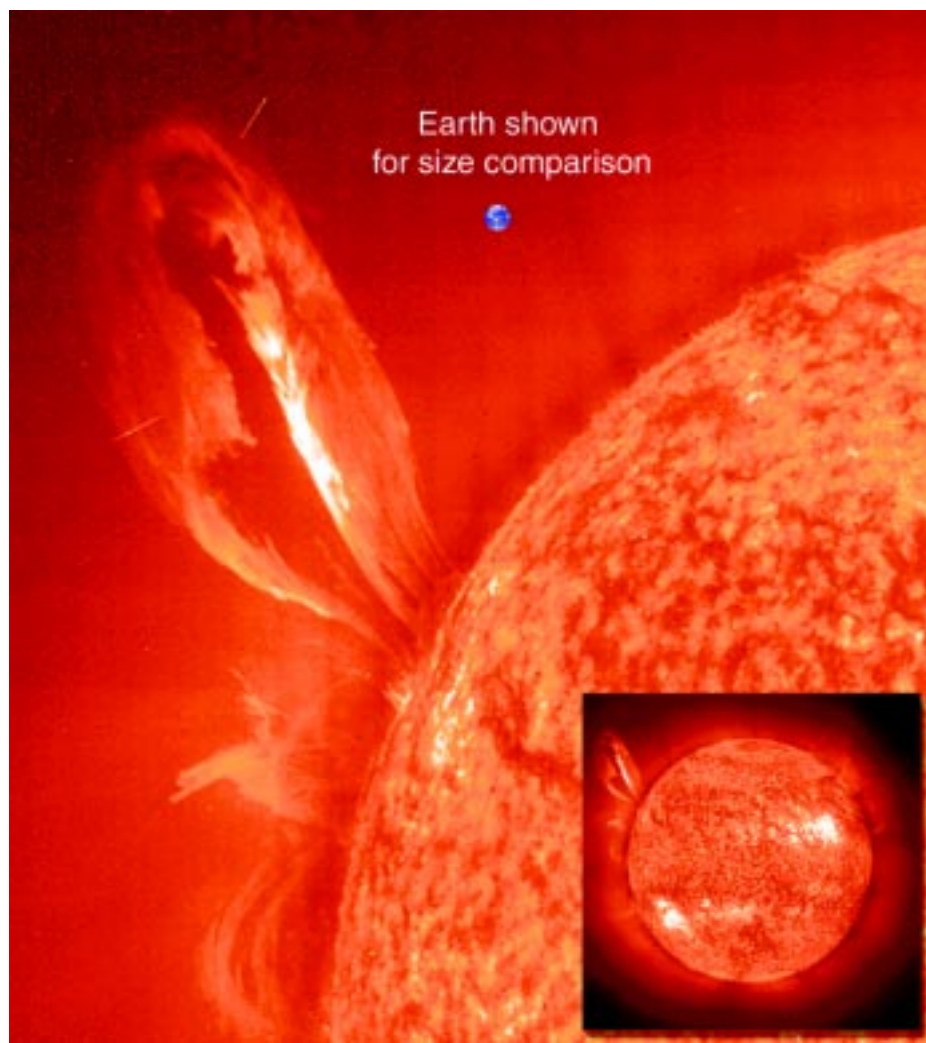
Just as seismology reveals the Earth's interior by

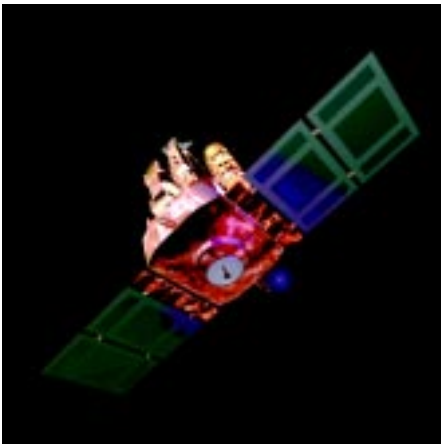
studying earthquake waves, solar physicists probe inside the Sun using a technique called 'helioseismology'. The oscillations detectable at the visible surface are due to sound waves reverberating through the Sun's interior, providing information about the structure and dynamics of the regions they pass through.

SOHO instruments have already revealed many unknown features of the interior, including layers where the speed of the gas changes abruptly and hidden jet streams circling the Sun's poles. SOHO has also made the first observations of seismic waves from a solar flare - on the surface the flare waves resembled ripples from a pebble thrown into a pond.

The availability of high spatial resolution data from SOHO/MDI opened a new window to look inside the Sun. 'Time distance helioseismology',

Large, eruptive prominence with an image of the Earth added for size comparison. This prominence from 24 July 1999 is particularly large and looping, extending over 35 Earths out from the Sun. Erupting prominences (when Earthward directed) can affect communications, navigation systems, even power grids, while also producing auroras visible in the night skies.





Weighing in at 1,850 kg, the SOHO satellite measures about 9.5 m across with its solar panels extended.

or 'solar tomography', is a new field in solar research which is developing primarily with SOHO/MDI data. It is one of the most exciting and most promising techniques for probing the 3-D structure and flows beneath the solar surface and offers the possibility of studying the birth and evolution of active regions below the Sun's surface as we approach solar maximum.

Currents of gas deep inside the Sun also appear to pulsate like the blood in human arteries, speeding and slackening every 16 months. The recent result comes from MDI observations combined with data from a worldwide chain of ground stations.

The observed variations in the flows of gas occur about 220,000 km beneath the visible surface - almost a third of the way down to the centre of the Sun. Here is the supposed dynamo region, where the turbulent outer region, the convection zone, meets the more orderly interior, the radiative zone. In this region, called the tachocline, the speed of the gas changes abruptly. Near the equator the outer layers rotate faster than the inner layers. At mid-latitudes and near the poles, the situation is reversed.

The new results show that the contrast in speed between layers above and below the supposed dynamo region can change by 20 per cent in six months. When the lower gas speeds up, the upper gas slows down, and vice versa.

In observations spanning 4.5 years, from May 1995 to November 1999, these alternations in speed occurred three times. They indicate a heartbeat of the Sun at one pulse per 15-16 months in equatorial regions, and perhaps faster at higher latitudes. This result is quite surprising, considering the much longer 11-year period observed in the sunspot cycle, thought to be governed by the same dynamo region.

Another SOHO instrument, called SWAN (short for Solar Wind Anisotropies), is capable of detecting active regions on the far side of the

The loss and recovery of SOHO

ESA SOHO deputy project scientist Pål Brekke recalls the dramatic events of two summers ago when the SOHO mission almost ended prematurely.

On 25 June 1998 at 04:43 UT our worst nightmare was beginning to unfold - contact with SOHO was lost, not to be re-established for more than six weeks. Through a series of unfortunate events the spacecraft had lost its sun-pointing attitude, which ultimately resulted in loss of power, telemetry and thermal control.

In one of the most dramatic recovery efforts in space, the SOHO recovery team - of more than 160 people drawn from ESA, Matra Marconi Space, NASA and AlliedSignal - succeeded in bringing the spacecraft back to normal sun-pointing attitude on 16 September 1998, after thawing the frozen hydrazine in the fuel tank, pipes and thrusters.

After re-commissioning all spacecraft subsystems, SOHO was brought back in normal mode nine days later. The re-commissioning of the scientific payload was successfully

completed on 5 November.

The fact that the spacecraft and the 12 instruments came through this ordeal almost unscathed is quite remarkable and constitutes a great tribute to the skill, dedication and professionalism of the scientists and engineers who designed and built them.

Two out of the three gyros on SOHO were damaged during this ordeal. When the last onboard gyro failed on 21 December 1998, SOHO went into Emergency Sun Reacquisition (ESR) mode.

In a race against time - the ESR thruster firings consumed an average of about 7 kg of hydrazine per week - engineers at ESTEC and Matra Marconi Space developed software to exit ESR mode without a gyro and allow gyroless operation of the spacecraft.

On 1 February 1999 a first gyroless reaction wheel management and station-keeping manoeuvre was performed, making SOHO the first three-axis-stabilised spacecraft to be operated without a gyro.



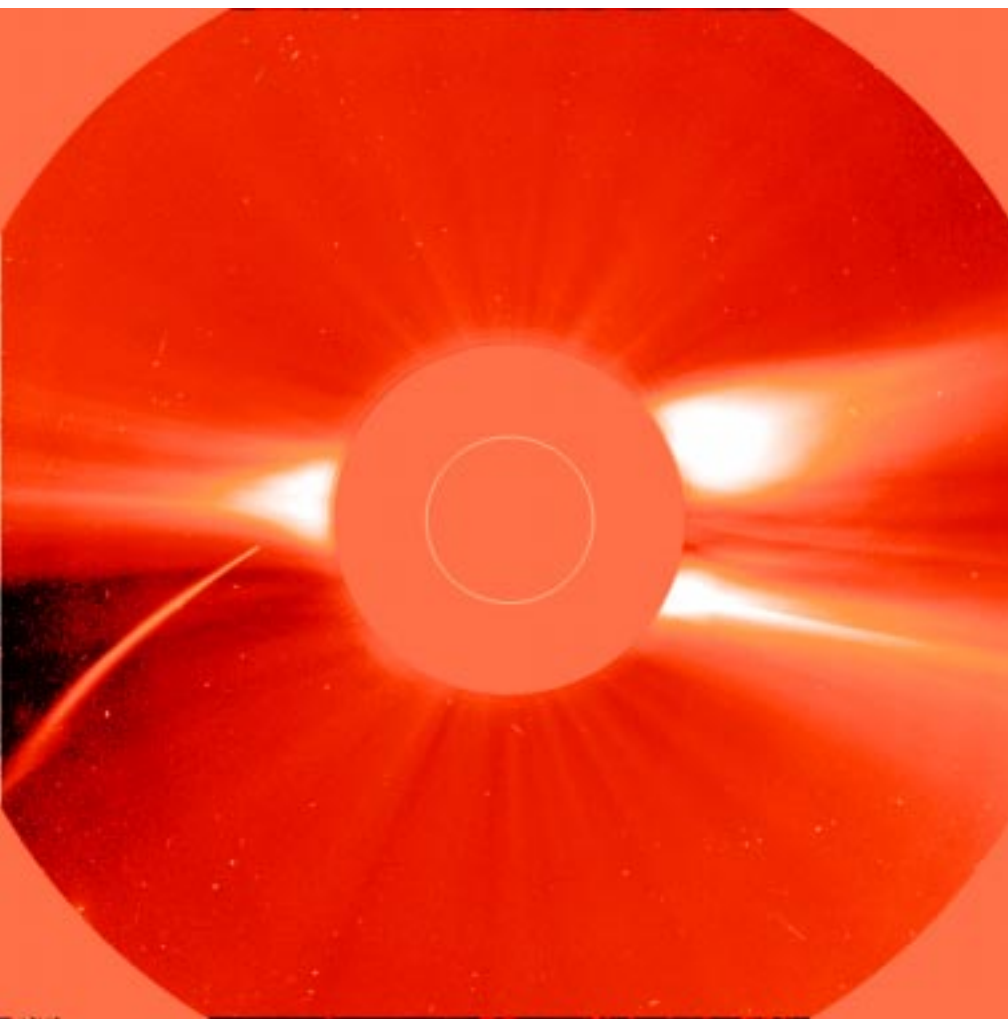
Sun. Mapping the whole sky in ultraviolet light, it sees a huge cloud of interstellar hydrogen that bathes the entire Solar System and interacts with the solar wind.

SWAN scientists have found that the hydrogen cloud beyond the Sun glows more strongly in the presence of active regions on the far side of the Sun compared to when there are no active regions. The enhanced emission from an active

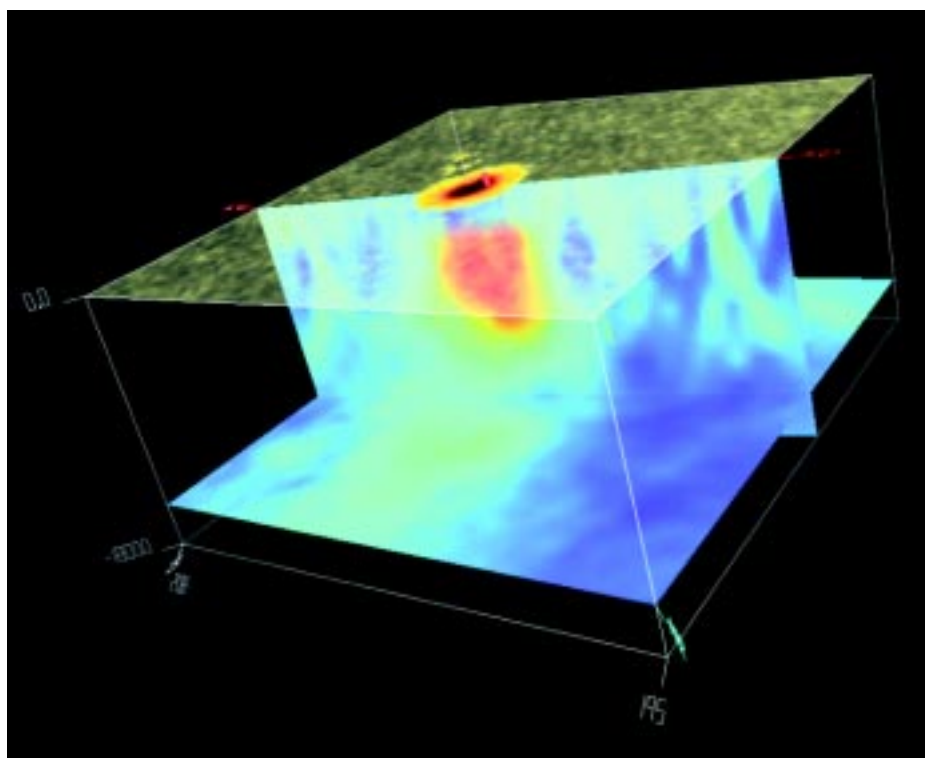
region on the far side of the Sun moves across the sky like a lighthouse beam as the Sun rotates.

Comet observations

Other instruments on SOHO have proved to be the most prolific comet finders in the history of astronomy. All but one of the SOHO comet discoveries were made with the LASCO



Comet SOHO-6, one of numerous sungrazing comets discovered by LASCO, as its head enters the equatorial solar wind region on 23 December 1996. It eventually plunged into the Sun. The field of view of this coronagraph encompasses 8.4 million kilometres of the inner heliosphere.



instrument, a set of coronagraphs that view the space around the Sun out to 20 million kilometres, while blotting out the bright solar disk with masks.

Until recently most of the comets had been discovered by the SOHO scientists, but since the images are now freely available on the Internet in almost real-time, the majority of over 200 comets discovered so far have been found by amateur astronomers.

Typically, comets observed by LASCO are 'Kreutz' sungrazers which do not survive their close encounter with the Sun. SOHO has increased the number of known sungrazer comets by a factor of eight, implying that there could be more than 20,000 fragments from the gradual break-up of a large comet.

Thanks to the near real time operation of SOHO, UVCS (short for Ultraviolet Coronagraph Spectrometer) has been able to capture the first ever space-based UV spectrometric observations of a comet's tail.

SOHO Comet 104 was discovered by LASCO on 9 February 2000 and observed by UVCS at four different heights above the limb the following day. These observations can be used to gauge the density of the corona at the position of the comet.

When comet Hale-Bopp flew near the Sun in 1997, parading its 100 million kilometres-long tail, it was also observed by the SWAN instrument. The scientists spotted a remarkable feature - never before seen by astronomers - the elongated shadow of a comet tail, more than 150 million kilometres long.

Water-ice in the comet's nucleus began to vaporise as Hale-Bopp approached the Sun. As expected, the Sun's ultraviolet radiation split the water molecules, liberating a cloud of hydrogen atoms that glow in the ultraviolet light. As the distance between the comet and the Sun quickly decreased, the release of vapour from the nucleus and the consequent production of hydrogen increased.

As a result, in a huge, 10 million kilometre-wide region around the nucleus, the comet absorbed most of the ultraviolet light coming

The subsurface structure (sound speed) below a sunspot as derived from Doppler measurements by MDI. Using the technique of time-distance helioseismology, three planes are shown. The surface intensity shows the sunspot. The second plane cuts from the surface to 24000 km deep showing areas of faster sound speed as reddish colours and slower sound speed as bluish colours. The third plane (bottom) is a horizontal cut at a depth of 22,000 km showing the horizontal variation of sound speed.

from the Sun. Thus, the comet projected a distinct shadow on the hydrogen haze of the Solar System. For an imaginary ultraviolet-eyed onlooker situated on the side of the comet opposite the Sun, it would have been a perfect opportunity to observe a total solar eclipse by a comet!

When the target for ESA's Rosetta mission (to be launched in 2003), Comet Wirtanen, made its most recent periodic visit to the Sun, it pumped out water vapour at a rate of 20,000 tons a day, according to the SWAN data.

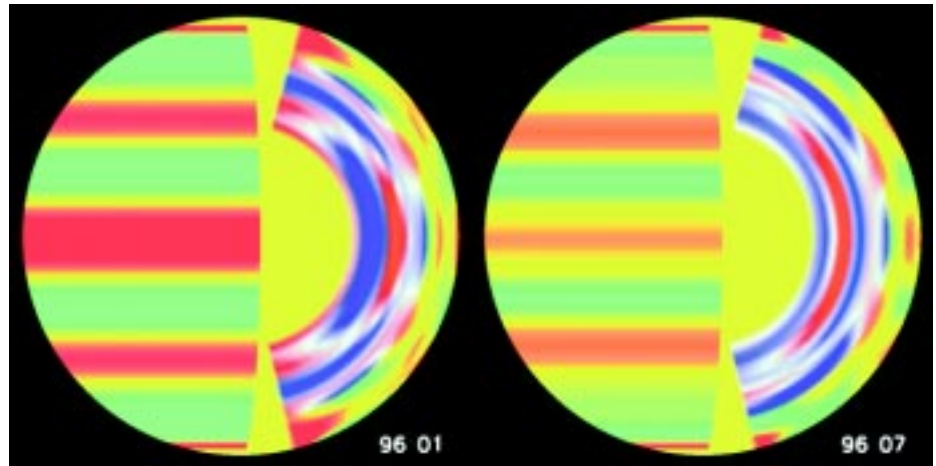
For the great Comet Hale-Bopp the rate reached 200 million tons a day, and SWAN watched its hydrogen cloud grow to 100 million kilometres - by far the largest object ever seen in the Solar System.

Such observations illustrate how SOHO, in addition to giving us new information about the Sun, is expanding our knowledge about the inner solar system and the physics of comets.

Space weather forecasting

The response of the space environment to the constantly changing Sun is known as 'space weather'. Most of the time space weather is of little concern in our everyday lives. However, when the space environment around the Earth is disturbed by the variable outputs of the Sun, technologies that we depend on can be affected.

Our society is much more sensitive to space weather activity today than was the case during



Currents of gas deep inside the Sun pulsate like the blood in human arteries, speeding and slackening every 16 months. Rotation rates near the bottom of the convection zone (white line), the level of the suspected dynamo, change markedly over six months. Faster/slower rates are shown in red/blue. Meanwhile near the surface (seen plainly on the left of each cutaway) bands of faster (red) and slower (green) rotation move towards the equator.

the last solar maximum in 1991. An example is the possible disruption of satellites.

We depend on satellites for weather information, communications, navigation, exploration, search and rescue, research, and defence systems. Thus, the impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate. Furthermore, safe operation of the International Space Station depends on timely warnings of eruptions on the Sun.

Two instruments on SOHO have proved to be especially valuable for continuous real-time monitoring of solar storms that affect space weather. One is the Extreme Ultraviolet Imaging Telescope (EIT) that provides images of the solar atmosphere at four wavelengths, revealing flares and other stormy events in the atmosphere.

The other is the Large Angle Spectrometric Coronagraph (LASCO) that takes images of the solar corona by blocking the light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. It is the perfect tool for detecting coronal mass ejections (CMEs) heading towards the Earth. CMEs are causing some of the most dramatic space weather effects.

SOHO has several times demonstrated its leading role in the early-warning system for space weather. Before SOHO was operational, only 27 percent of major magnetic storms were correctly forecast, and most forecasts were false alarms. The improvement offered by SOHO is apparent in a study of 25 front-side halo CMEs seen by LASCO and EIT during 1996 and 1997. Over 85 percent caused major magnetic storms and only 15 percent of such storms were not predicted.

The SOHO website has more information on the mission, recent science highlights and real time images: <http://sohowww.estec.esa.nl>

Pål Brekke, Bernhard Fleck, and Stein Haugan are members of the Solar System Division, ESA Space Science Department based at NASA/GSFC, Greenbelt, Maryland, USA.

Pal Brekke (standing) and Stain Haugan monitoring SOHO images of the Sun.

